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# SATELLITE ESTIMATES AND FORECASTS OF HEAVY RAINFALL FROM MESOSCALE CONVECTIVE SYSTEMS (MCSs)



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## 1. INTRODUCTION

Operational meteorologists and hydrologists need to know: how much rain has fallen, how much more will fall and the direction in which it will move. Currently, the question of how much rain has fallen is being determined by Synoptic Analysis Branch (SAB) meteorologists of NESDIS using the Interactive Flash Flood Analyzer (IFFA) system (Scofield, 1987 and Borneman, 1988). However, this system permits the computation of rainfall estimates for only one convective system at a time. This is due to the considerable time needed for image processing, interpretation and the computation involved in the estimation of rainfall. If there are several storms occurring (and this is typical in the summer season), an automatic estimation technique would be useful in providing "First Guess" rainfall estimates for the entire USA. Such an automatic technique (developed by NASA meteorologists, Adler and Negri, 1988) is being tested and implemented at NESDIS (Lyles and Scofield, 1989). This automatic technique is called the Convective-Stratiform Technique (CST). These "First Guess" estimates would alert the meteorologist as to which convective systems are producing the heaviest rains. As a result of the automatic estimates, the meteorologist could "zero in" on the potential flash flood producing storms and compute the more accurate interactive estimates.

Automatic estimates would also allow more time for SAB meteorologists to address the questions: how much more rainfall will occur and where will it move. This type of prediction involves determining where MCSs will propagate. Synoptic patterns associated with forward and backward propagating and regenerating Mesoscale Convective Systems (MCSs) have been identified. These patterns form the basis for a short range flash flood forecasting technique for MCSs.

This paper will show the relation between MCSs, rainfall and equivalent potential temperature ( $\theta_e$ ) patterns for heavy rainfall events over the USA between May-June, 1989. Along with the satellite imagery, $\theta_e$ patterns are a primary analysis "tool" used in the short range forecasting technique for MCSs. In addition, a case will be presented using the CST, Interactive and Short Range Forecasting Techniques.

## 2. DESCRIPTION OF TECHNIQUES

### 2.1 Convective-Stratiform Technique (CST) (Adler and Negri, 1988)

The CST is based on a one dimensional cloud model developed by Adler and Mack (1984). The technique uses 30 minute IR (10.5 - 12.6 um) data from the Geostationary Operational Environmental Satellite (GOES); resolution of the data is 8 km. The CST first defines the convective cores. This is done by reviewing GOES temperature array data and locating the minimum brightness temperature (Tmin). Using this Tmin location as the center point, (or centriod if the Tmin occurs at more than one point) then all points colder than their environment are considered thunderstorms or convective cores.

Secondly, minimum brightness temperatures are removed that represent thin and non-precipitating cirrus. To do this, a slope parameter is calculated from each $T_{min}$:

$$S = T_{1-6} - T_{min},$$

$$T_{1-6} = (T_{i-2,j} + T_{i-1,j} + T_{i+1,j} + T_{i+2,j} + T_{i,j+1} + T_{i,j-1})/6$$

where $T_{1-6}$ is the average temperature of the six closest pixels. A large slope represents the active part of the thunderstorm anvil; a small slope represents inactive cirrus debris.

Third, a rain rate and rain area are assigned t the location of the convective cores. This is based on the IR brightness temperature ($T_c$) and the cloud model approach of Adler and Mack (1984). The average rain rate ($R_{mean}$) over the

# 0-12 HOUR FORECASTING OF HEAVY RAINFALL FROM MESOSCALE CONVECTIVE SYSTEMS (MCSs)

## STEP 1

EXPECTED DEVELOPMENT

1. $(\text{Location of } \theta_e \text{ Ridge})_{sfc,\ 850,\ 700}$
(Examples of $\theta_e$ ridge axes are illustrated at the end)

ANALYZE

- o $\theta_e$ max
- o Primary Axes ($\theta_e$)
- o Secondary Axes ($\theta_e$)

AND

2. Locate any boundaries (meso- or synoptic) and areas where the NGM LI is: < 0 or becoming more unstable.

ASSOCIATED WITH 1. AND 2., LOCATE ANY OF THE FOLLOWING DESTABILIZATION PROCESSES

**HORIZONTAL ADVECTION (OFTEN AT NIGHT)**

- o $(\text{advection of } \theta_e)_{sfc,850,700} > 0$

**VERTICAL MOTION (DAY OR NIGHT)**

- o NGM VERTICAL MOTION>0
- o $(\text{positive vorticity advection})_{500}$
- o $(\text{moisture convergence})_{sfc,850}$
- o upper level speed max (jet streak)
- o mid-level vortices
- o upper level divergence

**SHEARING ADVECTION (OFTEN AFTERNOON)**

- o $\begin{Bmatrix}\text{temperature}\\ \text{advection}\end{Bmatrix}_{500} < 0$
- o $\begin{Bmatrix}\text{thermal}\\ \text{trough}\end{Bmatrix}_{500}$

**HEATING (AFTERNOON)**

- o $\left(\frac{\partial \theta_e}{\partial t}\right)_{sfc} > 0$

THE OPPOSITES OF THESE INHIBIT MCS DEVELOPMENT

$\theta_e$ = Equivalent Potential Temperature
NGM = Nested Grid Model
LI = Lifted Index

## STEP 2

EXPECTED MOVEMENT

### SLOW FORWARD PROPAGATING MCS

SATELLITE FEATURES

- o a slow eastward (usually southeastward) movement of MCS
- o colder IR tops in western portion of MCS
- o mergers often occur within the coldest top area

SURFACE AND UPPER AIR FEATURES

- o maximum 850 mb flow maintaining unstable air to western edge of MCS
- o a PVA center may or may not be present
- o thickness diffluence and near to just south of a weak-moderate thickness gradient
- o near to just south of stronger winds aloft
- o a surface boundary may or may not be present
- o MCS moves parallel to 850-300 mb thickness isopleths

### FAST FORWARD PROPAGATING MCS

SATELLITE FEATURES

- o a rapid eastward (usually southeastward) movement of MCS
- o colder IR tops in eastern, southern, or southwestern portion of MCS
- o mergers not usually detected

SURFACE AND UPPER AIR SATELLITE FEATURES

- o maximum 850 mb flow maintaining unstable air to leading edge of MCS
- o a PVA center present
- o northwest-southeast thickness isopleths present with a moderate gradient
- o MCS moves parallel to 850-300 mb thickness isopleths
- o a moderate to strong upper level flow pattern just north of area
- o a surface boundary may or may not be present

### BACKWARD PROPAGATING MCS

SATELLITE FEATURES

- o a synoptic or mesoscale boundary west of the MCS
- o colder IR tops in western portion of MCS and anvil debris in eastern portion
- o small convective cells along outflow boundary to west of MCS
- o cell mergers along boundary which in turn merge with MCS resulting in a westward moving MCS

SURFACE AND UPPER AIR FEATURES

- o MCS moves backwards along $\theta_e$ ridge axis
- o MCS moves backwards towards: higher $\theta_e$ values, higher temperatures between surface and 700 mb, lower instability, higher moisture and maximum low level winds
- o thickness diffluence and south of a west to east thickness pattern with a moderate gradient
- o PVA not normally present
- o weak upper level winds
- o veering of winds between surface and 850 mb

### REGENERATING MCSs

SATELLITE FEATURES

- o two or more MCSs develop and pass over same location within a 24 hour period
- o MCSs (often small and warm top) move eastward
- o MCSs often develop along a mesoscale or synoptic scale boundary

SURFACE AND UPPER AIR FEATURES

- o a persistent maximum 850 mb flow of the most unstable air into the area of MCS development (along a boundary that is west of flash flood area)
- o several weak 500 mb PVA centers oriented NE-SW over area
- o south of an east to west thickness pattern with a moderate gradient
- o south of the jet stream
- o MCS moves parallel to 850-300 mb thickness and/or $\theta_e$ ridge axis
- o weak middle to upper level winds
- o a weak surface boundary

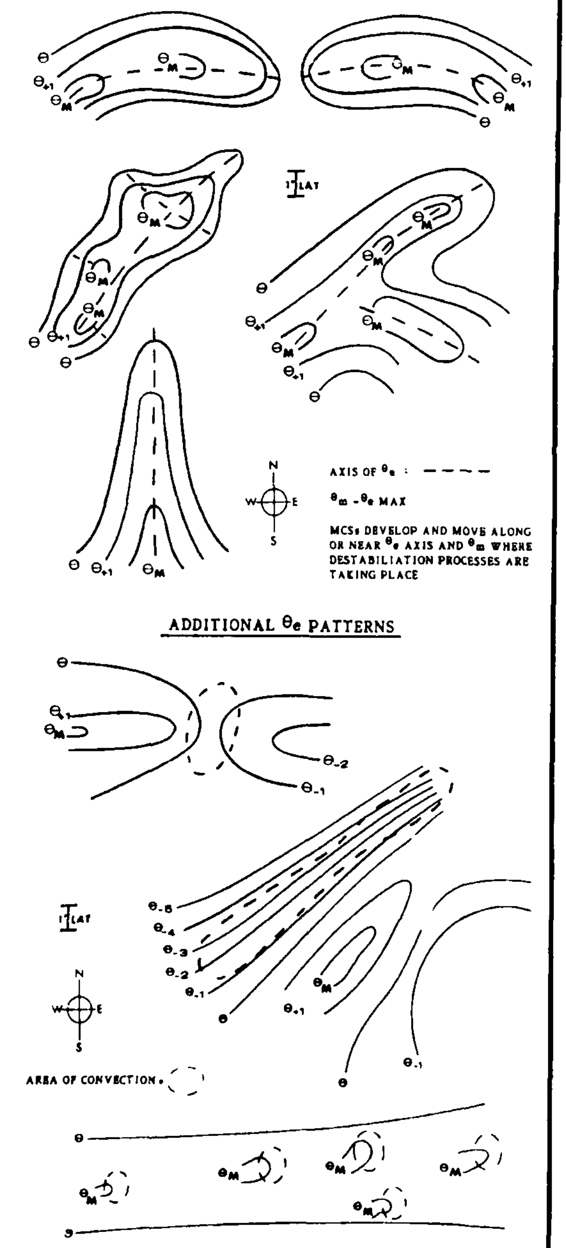
**STEP 3**

AVAILABLE AND EXPECTED MOISTURE

- o 1000-500 mb Precipitable Water $\geq$ 1.0.
- o 1000-500 mb Relative Humidity $\geq$ 60%.
- o Low Level Moisture Advection > 0.
- o Low Level Moisture Convergence < 0.

**STEP 4**

PATTERNS OF LOW LEVEL $\theta_e$ RIDGE AXES ASSOCIATED WITH MCS DEVELOPMENT & PROPAGATION




END OF TECHNIQUE

Figure 1. 0-12 Hour Forecast Technique Of Heavy Rainfall From Mesoscale Convective Systems.

raining area ($A_r$) of the cell is listed below:

$$R_{mean} = VRR/A_r$$

where VRR is the instantaneous volume rain rate.

Lastly, the anvil stratiform area is identified by a threshold value ($T_b$). This value of $T_{mode}$ is calculated from the satellite data:

$$T_S = E[W_i \cdot T_{mode(i)}]$$

where E[ ] is the expected value, $W_i$ is the number of IR pixels at $T_{mode(i)}$, and $T_S$ is the modal temperature. If there are any pixels less than $T_S$, the stratiform rainrate of 2 mm/hr is assigned.

### 2.2 0-12 Hour Forecasting Of Heavy Rainfall From MCSs (Jiang Shi and Scofield, 1987 and Xie Juying and Scofield, 1989)

A preliminary interactive short range flash flood forecasting technique for MCSs has been developed. The technique, presented in Figure 1, is divided into three parts: (1) Expected Development, (2) Moisture.

Expected Development (Step 1) is determined by: (a) locating the $\theta_e$ ridge axis at the surface and 850 mb, (b) locating any boundaries (meso- or synoptic) and areas where the Nested Grid Model Lifted Index is $\leq 0$ or becoming more unstable (boundaries are often located in the $\theta_e$ gradients) and (c) detecting destabilization processes (Instability Bursts) along: $\theta_e$ ridge axes, $\theta_e$ gradients and any type of meso- or synoptic scale boundary. Of course, downward vertical motion (subsidence) tends to "cancel out" destabilization (Instability Bursts) and inhibit MCS formation.

Expected Movement involves determining where the MCS will propagate: forward, backward or regenerate. Characteristic satellite, surface and upper air features associated with each type of propagation are listed in Step 2 (Figure 1).

Step 3 presents a list of moisture criteria for a MCS to produce heavy rainfall.

Finally, Step 4 presents examples of low level $\theta_e$ patterns associated with MCS development and propagation. The importance and relationships of $\theta_e$ patterns to MCSs and rainfall are discussed in the next section.

## 3. RELATIONSHIPS BETWEEN MCSs, RAINFALL AND $\theta_e$ PATTERNS (MAY - JUNE, 1989)

$\theta_e$ patterns are very useful in understanding MCS development and propagation (Scofield and Robinson, 1989).

The Meteorological Office at Bracknell, UK uses wet bulb potential temperature ( $\theta_w$ ) analyses and forecasts as one of their main tools for forecasting MCS development and movement. Bracknell's other main "tool" for tracking and forecasting MCSs is satellite imagery. Darkow (1968) has stated that $\theta_w$ and $\theta_e$ are almost interchangeable. From examining $\theta_e$ analysis for the past two summers on the NESDIS VAS* Data Utilization Center (VDUC), it appears that vorticity is to the synoptic scale system, what $\theta_e$ is to the MCS. Both are conservative, trackable and involved in the development, movement and propagation of their respective systems. MCS development and propagation can be expected with the following $\theta_e$ patterns: (1) $\theta_e$ ridge axes, (2) near areas of $\theta_e$ maxima or (3) within areas of $\theta_e$ gradients. The 850 mb and, sometimes, the 700 mb $\theta_e$ analyses are best for forecasting MCSs, often 6 to 12 hours before their occurrence. Surface $\theta_e$ analysis is a good tool for preparing hourly updates of $\theta_e$ patterns. However, surface $\theta_e$ patterns are often not as conservative, trackable and detectable as the 850 mb (or 700 mb) patterns. In addition, in overrunning synoptic or mesoscale boundary situations, surface $\theta_e$ is often useless. Of course for MCSs to develop, destabilization (an Instability Burst) has to occur with the above mentioned patterns.

The Table in Figure 2 shows the relationships between MCSs, rainfall and 850 mb $\theta_e$ patterns. $\theta_e$ patterns were related to precipitation signatures in the satellite imagery (Scofield, 1987). This Table was derived from 39 heavy rain "flash flood" producing MCSs during May - June, 1989 over the USA. The MCSs occurred east of the Rockies BUT west of the Appalachians. The 39 heavy rainfall events were divided into three categories of rainfall: 3-5.9 inches, 6-9.9 inches and 10-13.9 inches. These categories represent storm totals for a particular event and were obtained from the NMC 24 hour rainfall analysis used by NMC forecasters. The 3-5.9 inch category had 22 events, the 6-9.9 inch category had 9 events and the 10-13.9 inch category had 8 events.

Each MCS event was then classified as to its occurrence in a specific 850 mb $\theta_e$ pattern: (1) $\theta_e$ maximum (max) and ridge, (2) $\theta_e$ ridge, (3) $\theta_e$ gradient, (4) $\theta_e$ ridge and gradient, (5) $\theta_e$ max, ridge and gradient and (6) some other $\theta_e$ pattern, e.g., a $\theta_e$ minimum. In this study, 10% of the MCSs occurred in $\theta_e$ maxs and ridges, 38% in $\theta_e$ ridges, 26% in $\theta_e$ gradients, 18% in $\theta_e$ ridges and gradients, 3% in $\theta_e$ maxs, ridges and gradients and 5% in some other $\theta_e$ pattern. It has been our experience that during the summer, the 850 mb $\theta_e$ ridge axis is the most likely area for significant MCS development during the afternoon and evening. MCSs forming in

DISTRIBUTION OF MESOSCALE CONVECTIVE SYSTEMS (MCS)

*IN RELATION TO COMMONLY-OBSERVED 850 MB THETA-E PATTERNS*

(MAY - JUNE, 1989)

| MCS/Rain Category (Inches) | Max/ Ridge | Ridge | Gradient | Ridge | Max/Ridge/ Gradient | Other |
|---|---|---|---|---|---|---|
| 3-5.9 | 2 | 9 | 8 | 3 | | |
| 6-9.9 | 1 | 5 | 2 | 1 | | |
| 10-10.9 | 1 | 1 | | 3 | 1 | 2 |
| Total No. of MCSs | 4 | 15 | 10 | 7 | 1 | 2 |
| Percent | 10 | 38 | 26 | 18 | 3 | 5 |

Figure 2. Distribution Of Mesoscale Convective Systems In Relation To Commonly-Observed 850 mb Theta-E Patterns.

areas of $\theta_e$ gradients are often associated synoptically with: max $\theta_e$ advection areas, frontal boundaries and/or mid-upper level disturbances. These are often nocturnal events. For those MCSs occurring in $\theta_e$ ridge axes and gradients, the following scenario was noted. The convection usually began in the ridge, but in the course of development and expansion, spread into the adjacent gradient area. A similar scenario was observed for the MCS occurring in a $\theta_e$ max, ridge and gradient.

It is interesting that 64% of the MCS events occurred in either a $\theta_e$ ridge or gradient and that <u>95%</u> of the MCSs occurred within one or more of the following $\theta_e$ patterns: $\theta_e$ ridge axes, $\theta_e$ gradients and/or $\theta_e$ maxima. Five percent (2 cases) did not occur in these commonly observed 850 mb $\theta_e$ patterns. In one of these cases, the MCS was the remnants of a tropical disturbance and was related to the $\theta_e$ max and ridge axis at 700 mb while showing little relationship to the 850 mb $\theta_e$ ridge axis. This 700 mb $\theta_e$ ridge axis relationship has been observed with other tropical systems. In the other case, a massive MCS was located in a $\theta_e$ minimum and trough axis when the more likely location would have been the nearby $\theta_e$ ridge. More than likely, strong downdrafts from this massive MCS "brought down" lower $\theta_e$ air from mid-levels and replaced the higher $\theta_e$ air at 850 mb (Zipser, 1969). This is the same thermodynamic process that produces meso-highs and outflow boundaries.

## 4. MCS PRODUCING HEAVY RAINFALL EVENT OF JUNE 5, 1989

On June 5, 1989, MCSs produced heavy rain over Louisiana (LA), Mississippi (MS) and Tennesse (TN). IR imagery for 1200, 1400, 1600 and 1800 GMT are shown in

*VIS and IR Spin Scan Radiometer Atmospheric Sounder (VAS)

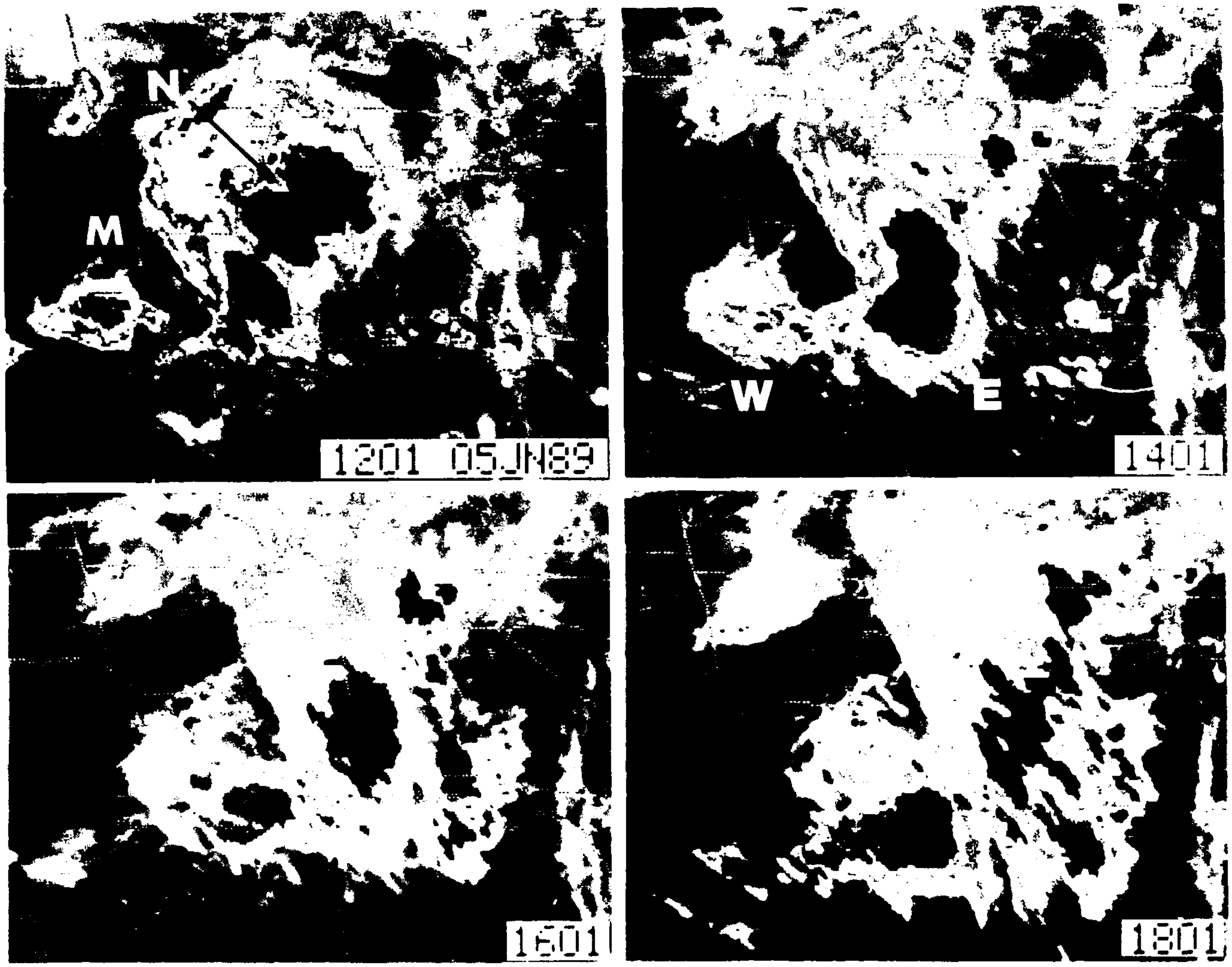


Figure 3. Enhanced IR Imagery (MB Curve) for 1200, 1400, 1600 and 1800 GMT, June 5, 1989.

Figure 3. The 850 mb $\theta_e$ analysis for 1200 GMT is illustrated in Figure 4. There are 3 primary $\theta_e$ maxs and are depicted as "1", "2" and "3"; ridge axes are indicated by dashed lines. Most of these $\theta_e$ max and ridge axes had some convection associated with them. However, due to environmental conditions and supporting dynamics (discussed later), the most pronounced MCSs (at "M" and "N" at 1200 GMT) are associated with the $\theta_e$ max and ridge axis over LA, MS and Alabama (AL). IR imagery at 1400, 1600 and 1800 GMT show new MCSs regenerating over southern LA and forming an east to west line of convection just north of the Gulf Coast (between "E-W" at 1400 GMT). In addition to the occurrence of the $\theta_e$ max and ridge, other conditions were favorable for the development and regeneration of these MCSs over LA and MS. Referring to the short range forecasting technique in Figure 1, these other favorable conditions along the Gulf Coast include:

- A "split flow" situation aloft; in the southern branch, 500 mb positive vorticity advection (PVA) was passing over extremely unstable air (Lifted Index of - 7 over LA) (this is a destabilization process or Instability Burst);

- Pronounced diffluence aloft and an upper level jet streak just west of the area (in the left-front quadrant);

- two or more MCSs developing and passing over the same location within a 12 hour period - a characteristic of regenerative MCSs (RM);

- MCSs developing along a outflow boundary (RM);

- At least two 500 mb PVA centers oriented NE-SW just north of the area (RM);

- MCSs moving parallel to the 850-300 mb thickness contours (RM) (1000-500 mb thicknesses could also be used); these thickness contours were also diffluent over LA;

- High values of 1000-500 mb precipitable water (1.57-1.90 inches);

- High values of 1000-500 mb relative humidity (68-80%).

Satellite-derived estimates were computed from the CST for a portion of this heavy rainfall event on June 5. The CST estimates were compared with the IFFA estimates where overlapping occurred.

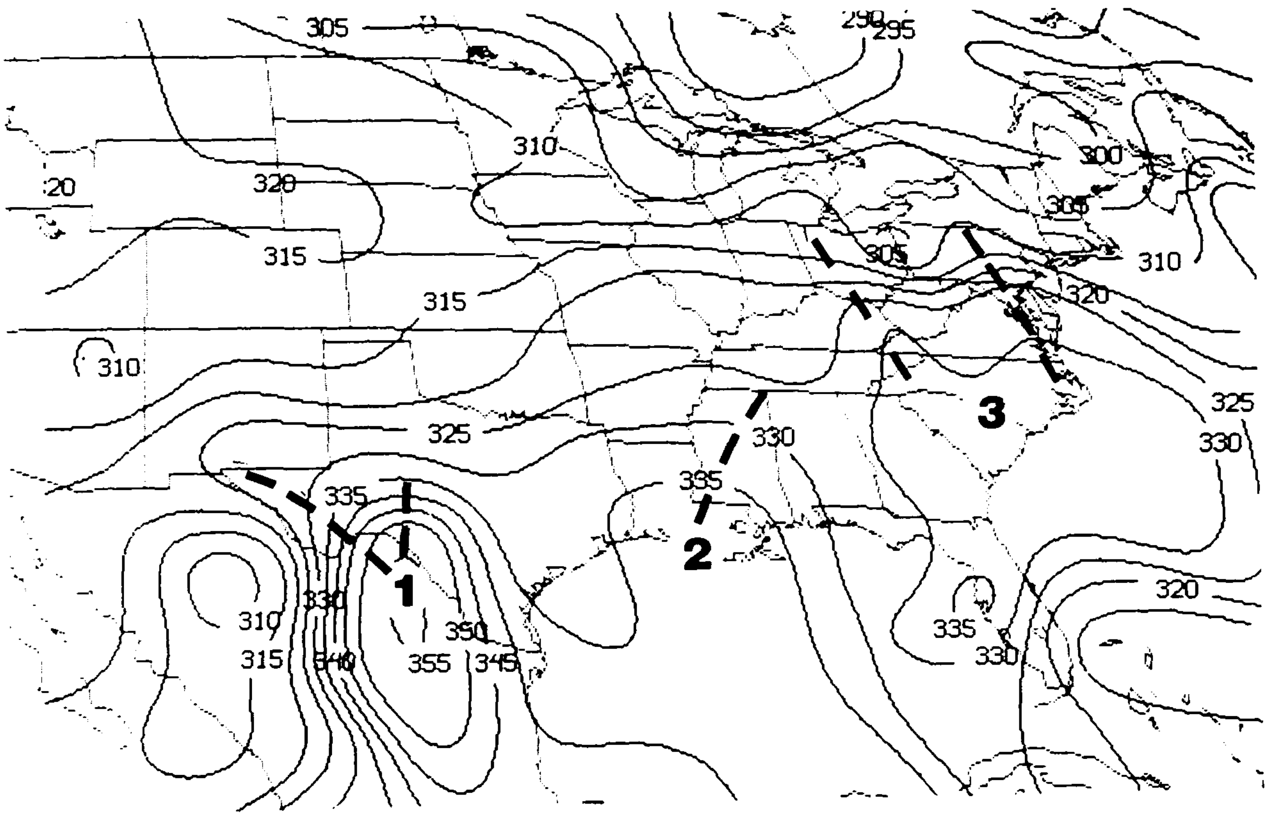



Figure 4. 850 mb Theta-E Analysis for June 5, 1989, 1200 GMT.

CST and IFFA estimates were computed for 1200-1500 GMT for the MCSs over LA and western MS; these are shown in Figures 5 and 6, respectively. Six hour and 24 hour observed rainfall are illustrated in Figures 7 and 8, respectively. The 24 hour rainfall analysis has many more observations as compared to the six hour one. Unfortunately, this 24 hour rainfall analysis is not available in "real time" but is used by NMC forecasters for verification. However, the six hour observations (Figure 7) are available in "real time". The 24 hour rainfall analysis depicted a 2-4 inch area of maximum rainfall over LA; the less dense six hour observations also showed a maximum over the same area BUT were much lighter. Most of the heavy rainfall over LA occurred between 1200-1600 GMT as the MCSs moved over southern LA and the Gulf Coast by 1800 GMT (Figure 4). It is obvious that both the CST and IFFA estimates are better correlated to the 24 hour observations than the six hour ones. The satellite estimates were able to analyze mesoscale areas of heavy rainfall which were not detected in the six hour "real time" rainfall network. Thus, the satellite estimates, which are "real time" measurements, are a useful "tool" for supplementing the less dense six hour observations. Radar data (not shown) indicated moderate to strong rainfall intensities near where the satellite estimates and rainfall observations had depicted the heavy rainfall.

The following is observed from comparing the CST and IFFA estimates and the observations:

(1) Both the CST and IFFA estimates depicted the area and amounts of heaviest rainfall as compared to the 24 hour observations;

(2) Both the CST and IFFA isohyetal patterns are similar;

(3) CST distributed the rainfall over a larger area compared to the IFFA estimates;

(4) The CST appeared to overestimate the magnitude of the rainfall in some areas;

(5) CST appears to be a useful "first guess" estimate as to where the heaviest rainfall is occurring and should be used to supplement the "real time" six hour rainfall observations.

## 5. SUMMARY AND OUTLOOK

Satellite data and the use of "pattern recognition techniques" for analyzing $\theta_e$ fields are important "tools" for estimating and forecasting heavy rainfall from MCSs. Of course, for MCSs to develop and propagate, destabilization (Instability Bursts) of the atmosphere has

to occur with specific $\theta_e$ patterns. In this study, 95% of the MCSs occurred within one or more of the following $\theta_e$ patterns: (1) $\theta_e$ ridge axes, (2) $\theta_e$ gradients and/or (3) $\theta_e$ maxima. Therefore, on most occasions, a forecaster should expect MCSs to be associated with one or more of these three $\theta_e$ patterns. The short range forecasting technique which uses all of the above information and more (Figure 1) is ready for field application by using AFOS (Automation Of Field Operations and Services) mesoscale analysis forecasting programs (Bothwell, 1988) and the SWIS (Satellite Weather Information System). $\theta_e$ cross section programs are available on AFOS (Barker, T., 1987); these cross sections would be useful in locating $\theta_e$ maxima, $\theta_e$ ridge axes and $\theta_e$ gradients.

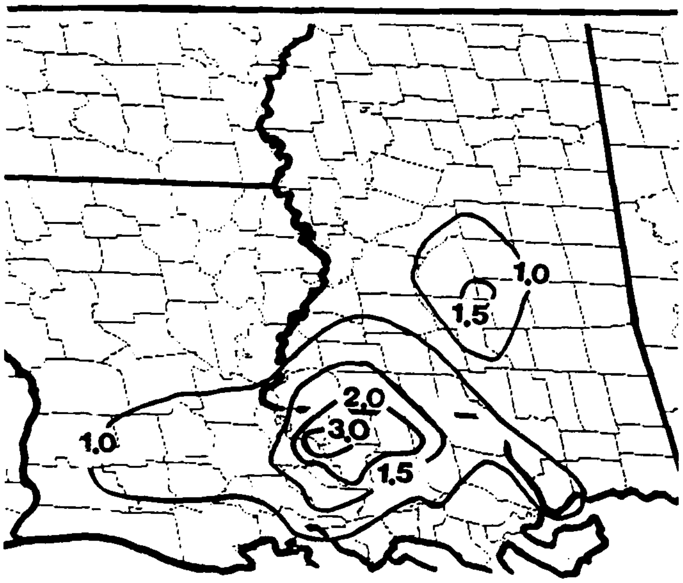



Figure 5. CST Estimates for 1200-1500 GMT, June 5, 1989.

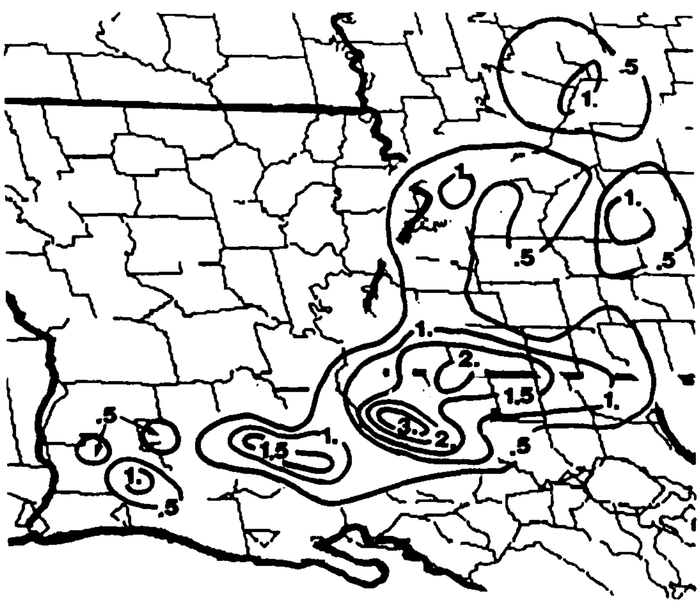



Figure 6. IFFA Estimates for 1200-1500 GMT, June 5, 1989.

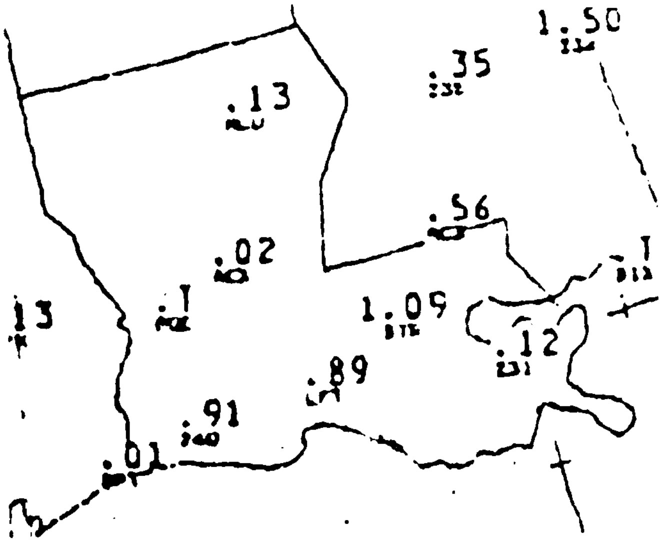



Figure 7. Six Hour Observed Rainfall Ending at 1800 GMT, June 5, 1989.

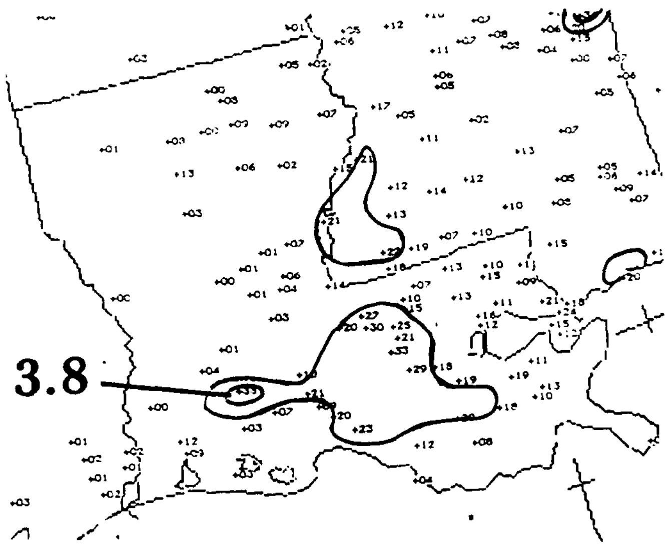



Figure 8. Twenty-four Hour Observed Rainfall Ending at 1200 GMT, June 6, 1989.

Experimental application of the CST on the VDUC has shown these estimates to be a good "first guess" as to which convective systems are producing the heaviest rains. As a result of these automatic estimates, meteorologists will be able to "zero in" on the potential flash flood producing storms and compute more accurate interactive estimates and short range forecasts.

This study only considered heavy rainfall MCSs for May-June, 1989. Data from July-September, 1989 has been collected on VDUC and is currently being analyzed and studied. A Tech Memo summarizing the results of this MCS investigation (between May-September, 1989) will be written and published in the near future.

## 6. ACKNOWLEDGEMENTS

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